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Abstract: Concrete has good fire resistance. However, once exposed to rapidly increasing temperatures, concrete may suffer from thermal stress-induced spalling or pore pressure-induced spalling. Compared with normal-weight concrete (NWC), lightweight aggregate concrete (LWAC) has a low thermal conductivity and is more prone to cause a higher temperature gradient under the action of high temperatures. This poses a hidden concern to the fire safety of general LWAC structures. Therefore, this study aimed to investigate the temperature and the pore pressure distribution of LWAC slabs under one-dimensional heating tests and to compare them with NWC slabs. The test variables were the moisture content of the specimen (oven-dried and air-dried), target temperature (600 and $800 \,^{\circ}\text{C}$), and heating rate (5 and $10 \,^{\circ}\text{C/min}$). The temperature and the pore pressure distributions were measured separately by thermocouples and pressure gauges embedded in different positions of the specimen. The test results show that the maximum pore pressure (P_{max}) of the LWAC slabs was generally higher than that of the NWC slab at a distance of 10 mm from the heated surface when the specimen was in an oven-dried state. However, at 30 and 50 mm from the heated surface, the P_{max} of the NWC slab tended to be higher. This shows that the P_{max} distribution of the LWAC slab was closer to the heated surface when the specimen was in an oven-dried state, while the P_{max} of the NWC slab occurred further from the heated surface. Further, as the heating rate increased, a higher pore pressure was generated inside the specimen and the pressure rose more rapidly. In particular, at a target temperature of 800 °C and a heating rate of 10 °C/min, the corner spalling phenomenon appeared on the air-dried LWAC slab.

Keywords: lightweight aggregate concrete; pore pressure; elevated temperature

1. Introduction

Concrete is one of the most widely used building materials today mainly because of its many advantages [1]. Concrete can be used in a variety of structures including high-rise buildings, tunnels, petrochemical plants, offshore platforms, bridges, nuclear plants, and other concrete structures. In essence, concrete has good fire resistance, and even if it is exposed to high temperatures or encounters fire damage, it still has a certain fire resistance [2]. However, concrete is a porous material filled with moisture and air. Once it is exposed to an intense heat flux incident, its mechanical properties deteriorate rapidly [3]. In view of this, many researchers have engaged in exploring the effect of high temperatures on the performance of various concretes [3–11].

Generally speaking, the composition of concrete can be divided into an aggregate, an interface transition zone (ITZ), and a cement matrix [1,2]. The properties of an aggregate are closely related to the unit weight, elastic modulus, and stability of concrete. In particular, the thermal properties of the aggregate play a key role in changing the volume of concrete that is subjected to high temperatures. Due to the presence of factors such as cement



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Copyright: © 2022 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). particle accumulation, bleeding, unidirectional growth, wall effects, and ion diffusion, the ITZ has properties different from the cement matrix. From a microscopic point of view, the cement matrix can be subdivided into solid and nonsolid microstructures, of which the solid microstructure mainly includes C-S-H gels, Ca(OH)₂, monosulfoaluminate, ettringite, unhydrated residual cement particles, chemically bound water, and gel pore water; nonsolid microstructures are mainly pores (capillary pores) and water (including capillary water, adsorbed water, and interlayer water) [1,2]. When concrete is subjected to fire damage and high temperatures, the microstructure and properties of its cement matrix will change with the increase in temperature [2,3]. As the temperature is between room temperature and 105 $^\circ$ C, the capillary water and adsorbed water are gradually lost. When the temperature is between 105 and 200 $^{\circ}$ C, the C-S-H gels begin to lose bound water and undergo chemical changes. As the temperatures increases to 250–350 °C, most of the bound water in the hydrate containing Al_2O_3 or Fe_2O_3 will be lost; approximately 20% of the bound water of the C-S-H gels will also be lost. At temperature between 400 and 700 °C, approximately 80% of the bound water in the C-S-H gels will be completely decomposed at this stage; however, at approximately 500 °C, the water in the matrix has been decomposed completely. In addition, the Ca(OH)₂ in the cement matrix begins to decompose at around 440–580 °C, but the reaction is reversible. As the temperature reaches 750 °C, the calcium carbonate in the calcareous aggregate begins to decompose and releases carbon dioxide; the quicklime (CaO) produced by the high temperature endotherm expands after absorbing water, which may cause cracks in the concrete. At temperatures between 800 and 1000 °C, the hydrates in the cement will be resintered to form the main components of cement such as C_2S , C_3A , and C_4AF . Once the temperature reaches 1425 °C, the remaining cement hydrate may be further sintered to form $C_3S[2,3]$.

When concrete is exposed to high temperatures, the loss of the stability of the cement matrix and aggregate affects its pore structure, and the physical and chemical changes that occur in the solid phase alter its pore size distribution and total porosity. After heating, the concrete's total pore volume does not increase linearly with temperature [12]. When the temperature reaches 300 °C, the increase in pore volume is smaller than the weight loss. Some scholars believe that it is caused by drying and hydrolysis processes. The structural change mainly occurs in pores with a pore size of less than 40 Å. When the temperature reaches 600 °C, the total pore volume will increase. However, some researchers have explored the relationship between porosity and temperature for concrete with different properties and found a linear one [13].

The effect of high temperature not only causes the volume of concrete to change but also causes the surface to peel off or spall. In particular, when high-strength concrete members are exposed to a rapidly rising temperature environment, they are more likely to spall, which will cause problems in the safety of concrete structures. The spalling of concrete can be divided into the following categories [14–18]:

- Explosive spalling, i.e., the most dangerous form;
- Destructive spalling, i.e., explosive in a few large pieces of concrete from the surface;
- Local spalling, i.e., a dislodging of minor pieces from some particular points of the surface;
- Sloughing off, i.e., a gradual reduction of a cross-section.

There are many researchers investigating the spalling mechanisms of heated concrete including thermal reactions (heat conduction), chemical reactions (the release of water and carbon dioxide), hygral reactions (the transport of water vapor or water), and mechanical reactions (microstructure damage, cracking, and thermal expansion differences) [19–24]. These reactions will result in the formation of dry/dehydrated, drying/dehydrating, and quasi-saturation regions in the concrete. The temperatures of these regions are also different, so the corresponding pore pressures are also different [18]. Some researchers believe that concrete may suffer from thermal stress-induced spalling or pore pressure-induced spalling [9]. Taking high-strength concrete as an example, during the heating process, pore vapor pressure is generated due to the evaporation and expansion of the internal water

but cannot be quickly dissipated. Furthermore, the water on the concrete's surface will be evaporated, and the water vapor inside the concrete will flow more into the interior of the porous medium due to the temperature gradient. When the temperature continues to rise, more water vapor diffuses inward, and the vapor content of the change layer between the low temperature and high temperature parts inside the porous medium will be saturated, thereby forming a moisture clog that prevents any gas flow from going further into the medium [25]. If the temperature continues to rise, under the interaction of pore pressure and thermal stress (caused by temperature gradients and external restraint conditions), spalling will occur once the internal pore vapor pressure exceeds the tensile strength of the concrete [6]. This results in a substantial reduction in the cross-sectional area of the concrete member and direct exposure of the reinforcement to flames, thereby reducing its load-bearing capacity [26].

In the past two decades, Taiwan has achieved good results in the use of reservoir sediments and industrial waste to make lightweight aggregate (LWA) that not only meets the environmental protection requirements of resource recycling and reuse but also improves the water storage function of the reservoir and prolongs its service life [27–33]. The particle density of synthetic LWA using reservoir sediments is significantly lower than that of normal density aggregates [28]. This is attributed to the fact that synthetic LWA particles have porous cores. They also meet the requirements of ASTM C 330 with a bulk density of coarse aggregate less than 880 kg/m³. In addition, the physical properties and crushing strength of the synthetic LWA are better than those of commercial LWA. This is due to the hard ceramic shell of synthetic LWA particles [28]. These results suggest that synthetic LWA can be used as an aggregate source for structural concrete. Further, light-weight aggregate concrete (LWAC) with excellent properties can be produced by using synthetic LWA, which can be applied to high-rise buildings and bridges to achieve the purpose of reducing self-weight and seismic force.

LWA is porous, has a low density, and has high water absorption; it is fired in a rotary kiln to a high temperature above 1000 °C. As a result, it has a higher thermal stability and a lower thermal expansion coefficient. Therefore, LWA is essentially different from normal-weight aggregate, which will lead to differences in the mechanical behavior and refractory performance of LWAC and normal-weight aggregate concrete (NWC) [34–38]. Uygunoğlu and Topçu [37] investigated the thermal expansion of self-consolidating normal and lightweight aggregate concrete at an elevated temperature varying from 20 to 1000 °C. The results showed that lightweight aggregate reduced the coefficient of thermal expansion of self-consolidating concrete due to the fact of its porous structure. Yao et al. [38] analyzed the mechanical properties degradation of LWAC after exposure to room temperature (20 °C) and high temperatures (up to 1000 °C). After exposure to 1000 °C, the LWAC lost no more than 80% of its strength, while the NWC lost its load-bearing capacity. Since LWA has many pores and a high water absorption rate, LWAC easily generates a high pore pressure inside it when it is exposed to a rapidly rising temperature environment. Coupled with a lower thermal conductivity, which contributes to a higher temperature gradient, LWAC members are more easily damaged under the action of a high temperature, which has a considerable impact on the fire safety of the structure [39-44]. Tang [44] pointed out that the presoaking degree of LWA had a significant effect on the residual compressive strength and elastic modulus of LWAC after exposure to 800 °C.

An overview of the above literature shows that concrete spalling at elevated temperatures is a complex phenomenon caused by the coupling of thermal, hydral, chemical, and mechanical processes. Under the standard temperature curve (ISO 834 standard fire resistance curve), the fire resistance of LWAC members (i.e., slabs, walls, and beams) is better than that of equivalent thickness members made with NWC. However, in the case of the hydrocarbon fire curve, fire tests showed the opposite result. This is because the factors that affect concrete's fire resistance include fire load (heat rate and maximum temperature), concrete properties (moisture content, permeability, and aggregate type), concrete strength grade (regular and high-strength concrete), and axial forces. Furthermore, relatively few studies have been conducted on the temperature and the pore pressure distribution of LWACs exposed to high temperatures. Therefore, this study aimed to investigate the temperature and the pore pressure distribution of LWAC slabs exposed to high temperatures. Thermocouples and pressure gauges were embedded in different positions of the slab specimens to measure their temperature and pore pressure, respectively. The test variables included the moisture content of the concrete specimen (oven-dried and air-dried), target temperature (600 and 800 °C), and heating rate (5 and 10 °C/min). In addition, NWC slabs of the same strength grade were used as a control group. The results of this study are helpful to understand the differences between LWAC and NWC in temperature and pore pressure distributions at elevated temperatures.

2. Experimental Procedure

2.1. Experimental Program

In this study, the temperature at depths of 0, 10, 30, 50, and 150 mm and the pore pressure at depths of 10, 30, and 50 mm from the heated surface of the specimen were measured. The test variables are listed below:

- Concrete type: LWAC (experimental group) and NWC (control group) were used to prepare slab specimens with a design strength of 40 MPa;
- Moisture content of the specimen: the state of the specimen before the high-temperature test included oven drying and air drying;
- Target temperature: the high-temperature test had two maximum temperatures (600 and 800 °C);
- Heating rate: two heating rates were used, a slow heating rate of 5 °C/min and a moderate heating rate of 10 °C/min.

2.2. Materials

The concrete materials used in this study were as follows:

- Cement: Portland Type I cement produced by Taiwan Cement Corporation was used. Its physical and chemical properties are listed in Table 1;
- Aggregate: The coarse aggregate was crushed stone made from natural pebbles in Taiwan, and its physical properties are listed in Table 2. The fine aggregate was natural river sand in Taiwan, and its physical properties are listed in Table 2;
- Lightweight coarse aggregate: A high-performance lightweight coarse aggregate of expanded shale was used, and its section is shown in Figure 1. Its physical properties are listed in Table 3;
- Superplasticizer: HPC-1000 produced by HICON. Its color was dark brown, specific gravity was 1.2, pH value was 7 ± 1 , and the solid composition was $42 \pm 2\%$.



Figure 1. The section of lightweight coarse aggregate.

Item	Content		
SiO ₂ (%)	20.21		
Fe ₂ O ₃ (%)	2.97		
Al ₂ O ₃ (%)	5.35		
CaO (%)	60.55		
MgO (%)	3.94		
SO ₃ (%)	2.51		
Specific gravity	3.15		
Specific surface area (cm^2/g)	3440		
Loss on ignition (%)	1.3		

Table 2. Physical properties of the aggregates used.

Туре	Specific Gravity (SSD)	Water Absorption (SSD) (%)	Dry Rodded Unit Weight (kg/m ³)	FM
Fine aggregate	2.59	1.60	-	2.58
Coarse aggregate	2.60	0.60	1451	-
CCD + 1 + 1 + 1	1 1°C EM C	1 1		

SSD: saturated surface-dry condition; FM: fineness modulus.

Table 3. Basic properties of the lightweight coarse aggregate used.

Particle Size	Particle Density (kg/m ³)	Water Absorp	otion (%)	Crushing Strength	
		30 min	24 h	(MPa)	
3/4"-4#	1410	7.1	10.5	8.6	
0/11	1110	<i>,</i> ,,,	1010		

2.3. Mix Proportions of the Concrete

According to the "Lightweight aggregate concrete reference guidelines for use and construction technology reference specifications" [45], the compressive strength of LWAC is divided into twelve grades, ranging from 5 to 60 MPa (i.e., LAC 5 to LAC 60), with a difference of 5 MPa for each grade. In this study, LAC 40 was used, that is, its designed 28-day compressive strength was 40 MPa, and its allowable variation range was 38–42 MPa. To compare the behavior of LWAC and NWC at high temperature, the same strength was used for both. Basically, the design principles of the mix proportions of structural LWAC and NWC are similar. The main difference is that LWAC needs to consider the influence of the density and water absorption of the lightweight coarse aggregate between different particle groups. Since the strength of lightweight aggregates is lower than that of ordinary aggregates, the LWAC used a lower water-cement ratio to achieve the same 28-day compressive strength as NWC. In addition, in order to make the prepared concrete have proper workability, different amounts of superplasticizers were used in the mix design of the LWAC and NWC. After several trial mixes, the mix designs of the LWAC and NWC were established, and they are shown in Table 4. The compressive strength of each age is shown in Table 5.

Table 4. Mix proportions of the concrete mixtures.

Min ID	W/C	Cement (kg/m ³)	Water	Water (30 min) * (kg/m ³)	Aggregates (kg/m ³)		SP	Unit Weight
MIX ID			(kg/m ³)		FA	CA	(kg/m ³)	(kg/m ³)
LWAC	0.36	450	203	40	690	568	3.60	1911
NWC	0.50	392	196	-	727	993	2.35	2310

* Water in quantity equal to 30 min of aggregate absorption. W/C: water/cement ratio; FA: fine aggregate; CA: coarse aggregate; SP: superplasticizer.

Mix ID –		Compressive S	Strength (MPa)	
	7 D	Days	28 I	Days
LWAC	33.0 31.0 34.8	(32.9)	39.7 36.1 39.0	(38.3)
NWC	28.2 26.6 27.3	(27.4)	40.0 40.3 39.3	(39.9)

Table 5. Compressive strength of the concrete.

2.4. Casting of Specimens

The mixing method for the NWC was as follows: The fine aggregate that was processed into a saturated surface-dry condition was added to a double-shaft mixer, and the cement was then placed in the mixer and fully dry-mixed at a speed of 45 rpm for approximately 1 min. Next, the water mixed with the superplasticizer was put into the mixer and mixed for approximately 1.5 min. The crushed stone that was processed into a saturated surface-dry condition was then placed into the mixer and mixed for another 1–2 min to obtain fresh concrete with uniform consistency. As for the LWAC, the mixing procedure was roughly the same, but the main difference was that the LWA had to be dried before it was mixed. This is because the water absorption rate of LWA varies greatly and is unstable. When immersed in water in a dry state, the instantaneous water absorption rate in the first few minutes is approximately 25–30% of the water absorption rate in 24 h. However, after 30 min, the water consumption was calculated according to the 30 min water absorption rate of the LWA.

After each group of concrete was mixed, its properties were tested immediately. Eight slab specimens (600 (length) \times 400 (width) \times 150 mm (thickness)) and six cylindrical specimens (diameter: 100 \times height 200 mm) were then cast for each group of concrete. There were embedded thermocouples and pressure gauges inside the slab specimen. The detailed configuration of the thermocouples (measuring temperature up to 1000 °C) and pressure gauges (model: MN1-6-M-B02C-1-4-D, its measuring range is 0–20 MPa) is shown in Figure 2. The specimen was disassembled after 24 h and then placed in a curing room with a temperature of 23 ± 2 °C. The specimens were not taken out until the day before the test age (28 days) for the high-temperature test and cylinder compressive strength test. For the test conditions in the air-dried state, the specimens were allowed to dry in the air for 24 h before the high-temperature test was performed. As for the test conditions of the oven-dried state, the specimen was first placed in an oven at 105 °C until its weight did not change.



Figure 2. Installation of thermocouples and pressure gauges in the slab specimens: (**a**) before pouring and (**b**) after pouring.

2.5. Test Methods and Instrumentation

To measure the temperature at different depths, K-type thermocouples (the highest measuring temperature can reach 1000 °C) were embedded in the slab specimen, and they were placed at depths of 0, 10, 30, 50, and 150 mm from the heated surface. In addition, at the center point, 100 mm above the center point, and 100 mm below the center point of the slab specimen to be poured, the depths were 10, 30, and 50 mm from the heated surface (as shown in Figure 3a). A thin steel tube with a diameter of 1.6 mm and a length of 200 mm was used. Referring to the pore pressure measurement method of Bangi and Horiguchi [46], a copper ring (12 mm in inner diameter and 3 mm in length) was welded to the edge of the end of these thin steel tubes, and the copper ring was filled with a porous sinter metal plate (as shown in Figure 3b). The plate could prevent the cement matrix from flowing back to the thin steel pipe when pouring the specimen so that the pore pressure at these positions could be measured correctly.



Figure 3. Scheme of the experimental setup: (**a**) arrangement of thermocouples and pressure gauges in the slab specimens; (**b**) structural diagram of the pressure pipe.

The heating of the concrete slab was made by a self-designed high-temperature electric furnace. The concrete slab was heated by one-way heating, and the pore pressure at different depths (10, 30, and 50 mm) of the heated surface and the temperature at the corresponding depth were measured (as shown in Figure 4). Before the test, the side of the slab specimen in the thickness direction was placed in a high-temperature furnace, and the surrounding of the specimen was wrapped in fireproof cotton to ensure that the concrete slab specimen was heated in one direction. Referring to the pore pressure measurement method of Bangi and Horiguchi [46], the inside of the pressure tube was filled with silicone oil. Therefore, the pore pressure could be transmitted smoothly, and the pressure gauge was then connected to the data acquisition junction box instruNET 100.



Figure 4. Specimen installation and sensor configuration.

On the other hand, thermocouples were placed at depths of 0, 10, 30, 50, and 150 mm from the heated surface to measure the temperature changes inside the specimen and the furnace, and the data were captured by the data acquisition system (GW Instruments). The high-temperature test used two different heating rates (as shown in Figure 5) until the maximum target temperature was reached. The duration of the 600 °C target temperature was 1 h, and the duration of the 800 °C target temperature was 2 h. The specimen was then cooled naturally to room temperature. During the test, the pore pressure and temperature were recorded at the same time, and the sampling rate was one instance of data acquisition every 10 s. Under the planned eight test conditions, each group of concrete slabs had only one specimen.



Figure 5. Schematic diagram of the heating rate of the high-temperature furnace: (a) 5 and (b) $10 \,^{\circ}\text{C/min}$.

A 500 kN MTS servo controlled universal testing machine (Eden Prairie, MN, USA) with a measurement accuracy of $\pm 1\%$ of the measurement range was used for the compressive strength test. The compressive strength test was carried out in accordance with the CNS 1232 specification. During the test, the cylindrical specimen was placed in the center of the compression shaft of the testing machine for loading, and the compression rate was between 0.14 and 0.34 MPa/sec until the specimen was destroyed. The compressive strength was obtained by dividing the ultimate load measured by the testing machine by the cross-sectional area of the cylindrical specimen, and the average value of three specimens was taken as the compressive strength of the group of cylindrical specimens.

3. Results and Discussion

3.1. Temperature Distribution of Concrete Slabs Exposed to High Temperatures

The high-temperature spalling of concrete is related to the thermo-mechanical process, which is associated with the temperature field and the thermal expansion mismatch between the cement matrix and the aggregate in the concrete [47]. Figure 6 shows the temperature evolution over time at 0, 10, 30, 50, and 150 mm from the heated surface of the LWAC slab under different test variables. In Figure 6, L stands for LWAC, OD stands for the oven-dried state of the specimen, and AD stands for the air-dried state; 600 and 800 are the two target temperatures ($^{\circ}$ C); R is the heating rate ($^{\circ}$ C/min), 5 means the heating rate was 5 °C/min, and 10 means the heating rate was 10° C/min. Figure 6 shows that the relationship between temperature development and time is an ascending branch followed by a descending branch, and the ascending and descending rates varied with the location of the measuring point. For the ascending branch, regardless of the test conditions, all of the curves associated with the thermocouples embedded in the specimen had different rates and increased nearly monotonically, with their relative positions consistent with the distance from the heated surface. In other words, the smaller the distance, the higher the temperature. Figure 6 also shows that, with the difference in the moisture content of the specimen, target temperature, heating rate, and depth from the heated surface, the temperature evolution was also quite different. Overall, under the condition that the moisture

content, target temperature, and heating rate were kept constant, the temperature rising rate of the heated surface of the concrete slab (i.e., 0 mm) was the fastest. The temperature rise rate on the back of the concrete slab (i.e., at 150 mm) was the slowest. The temperature rise rates at the remaining depths (i.e., 10, 30, and 50 mm) were between the heated side of the slab and the back of the slab.



Figure 6. Temperature distribution curves of the heated LWAC slabs: (a) L-OD-600-R5; (b) L-OD-600-R10; (c) L-AD-600-R5; (d) L-AD-600-R10; (e) L-OD-800-R5; (f) L-OD-800-R10; (g) L-AD-800-R5; (h) L-AD-800-R10.

On the other hand, it can be seen in Figure 7 that at a specific target temperature and heating rate, the temperature measured in the oven-dried state was roughly higher than that in the air-dried state. For example, at a target temperature of 600 °C and a heating rate of 5 °C/min, the maximum temperature of the heated surface of the oven-dried LWAC specimen was 466.7 °C, while the maximum temperature of the heated surface of the air-dried LWAC specimen was 383.6 °C. The temperature difference between the two was 83.1 °C. However, at a target temperature of 600 °C and a heating rate of 10 °C/min, the maximum temperature of the heated surface of the oven-dried LWAC specimen was 452.6 °C, while the maximum temperature of the heated surface of the air-dried LWAC specimen was 467.8 °C. The temperature difference between the two was only 15.2 °C. Moreover, Figure 8 shows that, under the conditions of a specific moisture content and a constant heating rate, the temperature rise rate of each measuring point of the specimen increased with the increase in the target temperature. In particular, when the target temperature was 800 °C, most LWAC slab specimens (including an oven-dried state and a heating rate of 10 °C/min; an air-dried state and a heating rate of 5 °C/min; an air-dried state and a heating rate of 10 °C/min) showed spalling. To avoid damage to the furnace, the test had to be stopped. Therefore, a complete temperature distribution curve could not be obtained, as shown in Figure 6f–h.



Figure 7. Comparison of the temperature distributions of the LWAC specimens at a target temperature of 600 °C: (**a**) heating rate of 5 °C/min; (**b**) heating rate of 10 °C/min.



Figure 8. Comparison of the temperature distributions of the oven-dried LWAC specimens: (a) heating rate of $5 \,^{\circ}$ C/min; (b) heating rate of $10 \,^{\circ}$ C/min.

Figure 9 shows that the temperature versus time curve of most of the measured points of the NWC specimen exhibited a slight plateau around 150–200 °C, that is, a perturbation of the temperature increase. These plateaus yielded worthwhile information on the hydral behavior of the specimens due to the phase change (vaporization) of water [40,48]. This transition was endothermic, resulting in the consumption of most of the energy from heating. Consequently, the heat transfer into the NWC slab slowed down. In addition, the

test results show that, under the same test variables, the temperature distribution trend of the LWAC slab was different from that of the NWC slab. It can be clearly seen in Figure 10 that the temperature of the LWAC slab was higher than that of the NWC slab at a depth of 10 mm. For example, the LWAC slab had a maximum temperature of 368.2 °C at a depth of 10 mm, while the NWC slab had a maximum temperature of 338.6 °C at a depth of 10 mm. This shows that the maximum temperature of the LWAC slab at a depth of 10 mm. This shows that the maximum temperature of the LWAC slab at a depth of 10 mm was 8.7% higher than that of the NWC slab. However, at depths of 30 and 50 mm, the temperature of the LWAC slab was lower than that of the NWC slab. For example, the LWAC slab had maximum temperatures of 273.7 and 220.2 °C at depths of 30 and 50 mm, respectively, while the NWC slab had maximum temperatures of 343.1 and 283.9 °C at depths of 30 and 50 mm, respectively. This shows that the maximum temperature of the LWAC slab at 30 and 50 mm depth was 20.2% and 22.5% lower than that of the NWC slab, respectively.



Figure 9. Comparison of the temperature distributions of the air-dried NWC specimens: (a) target temperature of 600 $^{\circ}$ C; (b) target temperature of 800 $^{\circ}$ C.



Figure 10. Comparison of the temperature distribution between the LWAC and NWC oven-dried specimens at a target temperature of 600 °C: (a) heating rate of 5 °C/min; (b) heating rate of 10 °C/min.

Moreover, Figure 11 shows a temperature gradient between each measuring point and the heated surface of the oven-dried specimens at a target temperature of 600 °C. It can be seen that different concrete specimens had different thermal gradients. For example, at a heating rate of 5 °C/min, the thermal gradient of the LWAC specimen at a distance of 10 mm from the heated surface was 12.4 °C/mm, while that of the NWC specimen was 10.4 °C/mm. The difference between the two was 2 °C/mm. This was due to the different properties of the aggregates in the two concretes. According to the literature, the thermal diffusivity of concrete is mainly controlled by the properties of the aggregate, as it occupies the highest volume fraction in the concrete composition [49]. Although Figure 11 shows an obvious temperature gradient inside the sample, there was no popping phenomenon. This result indicates that thermal stress caused by the temperature gradient alone was not

sufficient to cause explosive spalling. This is consistent with the results of Yang et al. [50]. It is worth noting that the greatest difference between the two concrete slabs is that when the maximum target temperature was 800 $^{\circ}$ C, the NWC slabs did not spall.



Figure 11. Comparison of the temperature gradients between the LWAC and NWC oven-dried specimens at a target temperature of 600 °C: (a) heating rate of 5 °C/min; (b) heating rate of 10 °C/min.

3.2. Explosive Spalling Phenomenon of Concrete Slabs Exposed to High Temperatures

Many factors affect concrete spalling or sloughing off including the moisture content, heating rate, thermal gradient, concrete strength, water-cement ratio, specimen size, aggregate type, and protective layer thickness [51,52]. The failure modes can be divided into aggregate spalling, corner spalling, surface spalling, and explosive spalling [53]. When the temperature of concrete subjected to fire damage reaches a certain value, its important mechanical properties will begin to decay rapidly with the increase in temperature. This temperature is called critical temperature. Therefore, the target temperature must include the critical temperature. This is mainly because when the concrete is exposed to a temperature of 400–600 °C, the cement hydration products in the matrix, namely, the C-S-H gels and C-H crystals, will decompose, resulting in a sharp drop in concrete strength [1,2]. However, when the high-temperature electric furnace is heated to the target temperature, the temperature it represents is the temperature in the furnace, not the actual temperature of the specimen. Therefore, the heating temperature of the electric furnace was increased to 600–800 °C as the target temperature of the high-temperature test so as to include the temperature range above and below the critical temperature. As for the high-temperature test, the furnace was heated to the target temperature at a rate of 5 $^\circ$ C/min and held for 1 h, and it was heated at a rate of 10 $^{\circ}$ C/min and held for 2 h.

In Table 6, according to the different test variables (i.e., the type of concrete, specimen's moisture state, target temperature, and heating rate), the spalling of the specimen or lack thereof during the high-temperature test is indicated. The table shows that the specimens with corner spalling in the test were all LWAC, and the target temperature was 800 °C. Figure 6f–h show that the thermal gradient of the heated surface of these specimens was large. This is because LWAC has a low thermal conductivity and a strong heat resistance effect, which caused a large temperature difference between the inside and outside of the specimen, resulting in a difference in the thermal expansion. This caused the concrete to peel off due to the tension, as shown in Figure 12. Corner spalling is a nonviolent form of spalling characterized by the separation of the concrete corners. It usually occurs late in the high-temperature test, mainly due to the loss of tensile strength due to the prolonged exposure to high temperatures [54].

Type of Concrete	Specimen Status	Target Temperature	Heating Rate	Remark
	Oven-dried	600 °C	5 °C/min 10 °C/min	Non-spalling Non-spalling
	oven uneu	800 °C	5 °C/min 10 °C/min	Non-spalling Corner spalling
LWAC	Air-dried -	600 °C	5 °C/min 10 °C/min	Non-spalling Non-spalling
		800 °C	5 °C/min 10 °C/min	Corner spalling Corner spalling
NWC	Oven-dried	600 °C	5 °C/min 10 °C/min	Non-spalling Non-spalling
	o ven aneu	800 °C	Non-spalling Non-spalling	
	Air-dried 600 °C 800 °C	600 °C	5 °C/min 10 °C/min	Non-spalling Non-spalling
		800 °C	5 °C/min 10 °C/min	Non-spalling Non-spalling

Table 6. High-temperature test results.



Figure 12. Corner spalling: (a) front view; (b) side view; (c) spalled concrete fragments.

As far as the influence of the state of the specimen and the heating rate is considered, when the target temperature was 800 °C, the LWAC spalled off only when the heating rate was 10 °C/min in the oven-dried state; in the air-dried state, spalling occurred regardless of the heating rate. This was due to the large thermal gradient formed on the surface of these specimens, which produced compressive stress in the direction parallel to the surface and tensile stress in the orthogonal direction [6]. Ouedraogo et al. [52] found that an indicative thermal gradient value of approximately 14 °C/mm was critical for spalling to occur. Table 7 shows that the temperature gradient between each measuring point and the heated surface of these specimens had exceeded the above critical value, resulting in corner spalling. For example, at a target temperature of 800 °C and a heating rate of 10 °C/min, the thermal gradient of the air-dried LWAC specimen at a distance of 10 mm from the heated surface was 25.44 °C/mm. This result confirmed that the corner spalling phenomenon in this study was closely related to the thermo-mechanical effect.

Type of	Specimen	Target Temperature	Heating Rate	Maximum Thermal Gradient (°C/mm)			
Concrete	Status			Depth fr	Depth from Heated Surface		
				10 mm	30 mm	50 mm	
LWAC –	Oven-dried -	600 °C	5 °C/min 10 °C/min	12.41 3.69	7.44 5.87	5.47 4.00	
		800 °C	5 °C/min 10 °C/min	10.15 11.61	7.82 12.27	7.30 8.60	
	Air-dried -	600 °C	5 °C/min 10 °C/min	0.02 16.00	2.59 5.42	3.77 5.48	
		800 °C	5 °C/min 10 °C/min	178.28 25.44	28.03 10.38	27.67 6.98	
NWC -	Oven-dried -	600 °C	5 °C/min 10 °C/min	10.43 7.17	3.39 5.04	3.40 4.31	
		800 °C	5 °C/min 10 °C/min	6.56 7.28	6.45 6.42	4.86 4.69	
	Air-dried -	600 °C	5 °C/min 10 °C/min	13.70 4.25	9.12 6.01	7.65 5.03	
		800 °C	5 °C/min 10 °C/min	12.97 25.80	8.65 10.46	7.72 8.21	

Table 7. Maximum thermal gradient.

3.3. Pore Pressure Distribution of the Concrete Slabs Exposed to High Temperatures

In addition to the thermo-mechanical process, the high-temperature spalling of concrete is also related to the thermo-hygral process, which is directly associated with the mass transfer of vapor, water, and air in the porous network [40,55]. In this study, pore pressure was a local measurement whose value depended on the location of the tube (in a cement matrix, near an aggregate, or in an air void). When the concrete slab was heated, three regions of dry/dehydrated, drying/dehydrating, and quasi-saturation were formed inside [40,56]. Due to the different temperature distributions in these regions, the corresponding pore pressures were also different, resulting in different degrees of cracking, flaking, or even spalling on the surface. Figure 13 shows the comparison of the pore pressure-time curves of the three measuring points in the LWAC slab under different experimental variables. Overall, under different test variables, the pore pressure measured at each measuring point of the specimen was also different. The measured pore pressures varied approximately between 77 and 2121 KPa, which were lower values compared to the data in the literature. In the case of Figure 13d, a pressure of 2121 kPa was measured at a depth of 50 mm from the heated surface of the air-dried specimen, even though there was no spalling. Furthermore, under certain experimental conditions, the pore pressure exhibited a sudden drop, as shown in Figure 13d,f-h. This was caused by the rapid escape of moisture vapor into the atmosphere as the concrete fragments peeled off the heated surface.



Figure 13. The build-up of pore pressure with time for the LWAC slabs: (**a**) L-OD-600-R5; (**b**) L-OD-600-R10; (**c**) L-AD-600-R5; (**d**) L-AD-600-R10; (**e**) L-OD-800-R5; (**f**) L-OD-800-R10; (**g**) L-AD-800-R5; (**h**) L-AD-800-R10.

The evolution with time of the temperature and pore pressure at a depth of 30 mm from the heated surface of the LWAC slabs at a target temperature of 600 °C and a heating rate of 5 °C/min is shown in Figure 14. The figure shows that the peak value of the measured pore pressure was reached in the vaporization temperature range. This result suggests that the vaporization of water into the concrete was responsible for the increase in pore pressure. The diffusion of heat in the specimen and the resulting complex hygral behavior created a zone of saturation close to the exposed surface (i.e., moisture clog) [48].



Figure 14. The evolution with time of the temperature and pore pressure at a depth of 30 mm from the heated surface of the LWAC slab at a target temperature of 600 $^{\circ}$ C and a heating rate of 5 $^{\circ}$ C/min: (a) oven-dried state; (b) air-dried state.

Figure 15 compares the pore pressure and saturated water vapor pressure curves of the LWAC slabs. Essentially, the saturated water vapor pressure is a function of temperature, which is the maximum pressure of water vapor at a certain temperature. From the relationship between the pore pressure and the saturated water vapor pressure curves, it can be divided into three stages. The first is called the supersaturated state, which represents a state where the pore pressure is higher than the saturated water vapor pressure. The second is called the saturated state, which represents the state where the pore pressure is equal to the saturated water vapor pressure. The third is called the unsaturated state, which represents the state where the pore pressure is lower than the saturated water vapor pressure. By comparing the saturated water vapor pressure and the pore pressure in the specimen, its moisture state change, water vapor amount, and moisture migration could be determined [57,58]. Figure 15 shows that the water vapor of the oven-dried specimen at 10 mm was unsaturated. As for the air-dried specimen, under the condition of a heating rate of 10 °C/min, whether the target temperature was 600 or 800 °C, the water vapor at 10 and 50 mm was supersaturated. This was due to the contribution of the partial pressure of the dry air enclosed in the pores of the specimen [59]. In contrast, at a heating rate of $5 \,^{\circ}$ C/min, the water vapor at 50 mm was unsaturated. It is worth noting that spalling also occurred when the water vapor pressure in the specimen was in an unsaturated state. This was because the pores in concrete consist of water in the form of free water, water vapor, and dry air. If the temperature distribution inside the concrete is uniform, the water vapor pressure in the pores increases without creating a pressure gradient between the pores, thereby raising the boiling point of water [58]. Therefore, the water remained liquid and did not evaporate, resulting in an unsaturated state of water vapor pressure.



Figure 15. Comparison between the pore pressure and saturated vapor pressure curves.

On the other hand, Figure 13 shows that the relationship between pore pressure and time basically consisted of an ascending branch followed by a descending branch, and the ascending and descending rates varied with the location of the measuring point. The ascending branch could be explained as a result of the formation of a fully saturated layer during the transport of moisture to the deeper, cooler regions of the heated concrete, which prevented further transport of moisture vapor, resulting in a build-up of pore pressure at the saturated front [60]. Due to the formation of the moisture clog, the vapor flow would only flow to the heated surface. In addition, the concrete located between the heated surface and the moisture clog continued to dry and dehydrate. Once the rate at which the vapor escaped from the pores was higher than the rate at which the vapor (from drying, dehydration, and transport) filled the pores, the pressure began to drop [48]. At the same time, cracking might also lead to a decrease in pore pressure by creating more usable volume in the matrix, especially by increasing the permeability of the material such that vapor can escape [61]. These two phenomena could explain the shape of the pore pressure curve. In order to further understand the influence of various test variables on the pore pressure distribution of concrete slabs, the following subsections analyze and discuss the test results under different test conditions.

3.4. The Effect of the Target Temperature on the Pore Pressure

3.4.1. The Effect of the Target Temperature on the Pore Pressure of the Oven-Dried Specimens

The evolution of the pore pressure at a depth of 10 mm from the heated surface of ovendried specimens at a heating rate of 5 °C/min is shown in Figure 16a. With the increase in the target temperature (from 600 to 800 $^{\circ}$ C), the maximum pore pressure of the LWAC slab increased significantly from 102 to 143 KPa, while the maximum pore pressure of the NWC slab increased from 85 to 109 KPa. Furthermore, under the same target temperature conditions, the pore pressure of the LWAC slab at a depth of 10 mm was higher than that of the NWC slab. As for the depths of 30 and 50 mm from the heated surface of the concrete slab, the evolution of the pore pressure is shown in Figure 16b,c. With the increase in the target temperature, the pore pressure of the LWAC slab still increased significantly there, as did the NWC slab. For example, when the target temperature was raised from 600 to 800 °C, the maximum pore pressure at a depth of 30 mm for the LWAC slab increased significantly from 82 to 153 KPa, while the maximum pore pressure at a depth of 30 mm for the NWC slab increased from 138 to 194 KPa. From the above results, a higher target temperature could cause the maximum pore pressure to occur further from the heated surface. This is because the water vapor from the depth of the heated surface was less likely to transfer, and the higher target temperature could cause the free water trapped in the matrix to evaporate. Therefore, its pore pressure could be increased. However, under the same target temperature conditions, the pore pressures of the LWAC slab at depths of 30 and 50 mm were lower than those of the NWC slab. This situation is opposite to the

aforementioned case with a depth of 10 mm from the heated surface of the specimen, and this may be due to the low thermal conductivity of LWAC. This can be seen in Figure 10; the temperatures of the LWAC slab at depths of 30 and 50 mm were lower than those of the NWC slab; thus, the pore pressure of these measuring points was also relatively low.



Figure 16. Effect of the target temperature on the pore pressure of oven-dried specimens performed at a heating rate of 5 $^{\circ}$ C/min: (**a**) 10; (**b**) 30; (**c**) 50 mm depths.

Figure 17a shows the evolution of the pore pressure at a depth of 10 mm from the heated surface of oven-dried specimens performed at 10 °C/min. Under the condition of a target temperature of 600 °C, the pore pressure of the LWAC slab at a depth of 10 mm was higher than that of the NWC slab. When the target temperature was increased from 600 to 800 °C, the pore pressure of the LWAC slab increased sharply after being heated for 1 h and then spalled. After 2 h, the pore pressure decreased rapidly due to the spalling, and its value was even lower than the value at 600 $^{\circ}$ C. When the heating rate was increased from 5 to 10 °C/min, the LWAC slab spalled, which resulted in the temperature evolution curve shown in Figure 6f. In contrast, increasing the heating rate did not cause the NWC slab to spall. As for a depth of 30 mm from the heated surface of the concrete slab, the evolution of the pore pressure is shown in Figure 17b. At a target temperature of 600 °C, the pore pressure evolution curve of the slab was relatively gentle, and the pore pressure of the LWAC specimen was smaller than that of the NWC specimen. When the target temperature was 800 °C, both the LWAC and NWC slabs had high pore pressures, and the pressure rose sharply. The pore pressure dropped rapidly, and its value was even lower than the value at 600 °C. This result suggests that high-temperature-induced cracks may help to increase the permeability of the specimen to evacuate water and reduce pore pressure. However, at 50 mm from the heated surface (Figure 17c), a larger pore pressure was generated when the target temperature was 600 °C. In contrast, when the target temperature was 800 °C, cracks formed on the surface of the specimen due to the severe fire damage. As a result, the internal gas escaped more easily; thus, there was a lower pore pressure at 50 mm.



Figure 17. The effect of the target temperature on the pore pressure of the oven-dried specimens performed at a heating rate of $10 \,^{\circ}\text{C/min}$: (a) 10; (b) 30; (c) 50 mm depth.

3.4.2. The Effect of the Target Temperature on the Pore Pressure of the Air-Dried Specimens

Figure 18a shows the evolution of the pore pressure at a depth of 10 mm from the heated surface of the air-dried specimens when the heating rate was 5 $^{\circ}$ C/min. It can be seen that the LWAC slab had similar pore pressure evolution curves at the target temperatures of 600 and 800 °C. As for the NWC slab, a steep rise in the pore pressure occurred at a target temperature of 600 °C. However, it declined rapidly, which meant that micro-cracks generated at 10 mm. In contrast, its pressure curve at 800 °C was relatively flat. Figure 18b shows that the pore pressure curve of the LWAC slab at a target temperature of 600 $^{\circ}$ C was slightly higher than its 800 $^{\circ}$ C curve at a distance of 30 mm from the heated surface. The reason for this may be that cracks formed on the surface of the specimen due to the intense fire damage at 800 °C, which made the internal gas escape more easily and reduced the pore pressure. In contrast, the pressure curve of the NWC slab at a target temperature of 800 °C was significantly higher than that at 600 °C. At a distance of 50 mm from the heated surface, Figure 18c shows that when the target temperature was 600 °C, the pore pressure evolution curves of both the LWAC and NWC slabs were relatively flat. However, both the LWAC and NWC slabs had larger pore pressures at a target temperature of 800 °C, and the LWAC slab had a more obvious pressure rise. Figure 19a shows the pore pressure curve at 10 mm from the heated surface when the heating rate was $10 \,^{\circ}\text{C/min}$. The pore pressure generated by the LWAC slab at a target temperature of 800 °C was higher than that at 600 $^{\circ}$ C, and the pressure rise was very obvious. The NWC slab had a higher pore pressure when the maximum fire temperature was 600 °C. At 30 mm from the heated surface, Figure 19b shows that the LWAC slab had a higher pore pressure at a target temperature of 600 °C. On the other hand, the pore pressure of the NWC slab was relatively large at 800 °C, and the pressure rose sharply after being heated for 1 h. Figure 19c shows that at a distance of 50 mm from the heated surface, both the LWAC and NWC slabs generated larger pore pressures at a target temperature of 600 °C.



Figure 18. Effect of the target temperature on the pore pressure of air-dried specimens performed at a heating rate of $5 \degree C/min$: (a) 10; (b) 30; (c) 50 mm depths.



Figure 19. Effect of the target temperature on the pore pressure of air-dried specimens performed at a heating rate of 10 °C/min: (**a**) 10; (**b**) 30; (**c**) 50 mm from the heated surface.

3.5. The Effect of the Heating Rate on the Pore Pressure

3.5.1. The Effect of the Heating Rate on the Pore Pressure of the Oven-Dried Specimens

The literature shows that an increase in the heating rate tends to lead to a higher risk of spalling [19]. This is because the higher thermal gradient accelerates the build-up of pore pressure near the exposed surface. The evolution of the pore pressure at a depth of 10 mm from the heated surface of the oven-dried specimens at a target temperature of $600 \,^{\circ}\text{C}$ is shown in Figure 20a. With the increase in the heating rate (from 5 to $10 \,^{\circ}\text{C/min}$), the maximum pore pressure of the LWAC slab increased significantly from 102 to 126 KPa, while the maximum pore pressure of the NWC slab increased from 85 to 94 KPa. This is consistent with the view of classical theory. That is, in the absence of surface cracking and severe concrete damage, an increase in the heating rate should lead to an increase in the vapor transport rate and an increase in the accumulation of moisture vapor, leading to the formation of a saturated zone and, thus, an increase in the pore pressure [46]. From the pore pressure curve of the LWAC specimen with a heating rate of 10 °C/min, the pressure value jumped greatly after being heated for 3 h. This means that cracks were created inside it, resulting in a decrease in the pore pressure. If the pressure curves are compared, it can be clearly seen that the faster the heating rate, the faster the pressure curve rises. This is because a faster heating rate causes the internal temperature of the specimen to rise faster, resulting in a faster rise in the pore pressure. Furthermore, under the same heating rate, the pore pressure of the LWAC slab at a depth of 10 mm was higher than that of the NWC slab. As for the depths of 30 and 50 mm from the heated surface of the concrete slab, the evolution of the pore pressure is shown in Figure 20b,c. These figures show that with the increase in the heating rate, the pore pressure of the LWAC slab still increased significantly, and the same was true for the NWC slab. For example, when the heating rate was raised from 5 to 10 °C/min, the maximum pore pressure at a depth of 30 mm for the LWAC slab increased significantly from 82 to 99 KPa, while the maximum pore pressure at a depth of 30 mm for the NWC slab increased from 138 to 150 KPa. The above results show that a faster heating rate led to a higher pore pressure and pressure rising rate. This is in agreement with the findings of Bangi and Horiguchi [46].



Figure 20. Effect of heating rate on the pore pressure of oven-dried specimens performed at a target temperature of 600 °C: (**a**) 10; (**b**) 30; (**c**) 50 mm depths.

The evolution of the pore pressure at a depth of 10 mm from the heated surface of the oven-dried specimens at a target temperature of 800 °C is shown in Figure 21a. It can be seen that the pore pressure generated by the LWAC slab with a heating rate of 10 °C/min was higher than that with a heating rate of 5 °C/min. In addition, the pressure curve showed a steep rise when heated for 1 h. However, the NWC slab had a higher pore pressure with a heating rate of 5 °C/min. At a depth of 30 mm from the heated surface (as shown in Figure 21b), both the LWAC and NWC slabs generated a large pore pressure when the heating rate was 10 °C/min, and the pressure in both cases rose rapidly. The peaks were evident from these pressure curves but then dropped rapidly. This result indicates that there was an internal crack due to the high temperature, which caused the pressure to dissipate quickly. At a distance of 50 mm from the heated surface (as shown in

Figure 21c), both the LWAC and NWC slabs generated larger pore pressures at a heating rate of 5 °C/min. This is consistent with Phan's findings [62]. This is because when the heating rate was 10 °C/min, a large crack formed at a depth of 30 mm; therefore, the pressure value at a distance of 50 mm from the heated surface dissipated more easily. Furthermore, under the same heating rate at this depth, the NWC slab had a higher pore pressure.



Figure 21. Effect of the heating rate on the pore pressure of the oven-dried specimens performed at a target temperature of 800 °C: (**a**) 10; (**b**) 30; (**c**) 50 mm depths.

3.5.2. The Effect of the Heating Rate on the Pore Pressure of the Air-Dried Specimens

The evolution of the pore pressure at a depth of 10 mm from the heated surface of the air-dried specimens at a target temperature of 600 °C is shown in Figure 22a. The maximum pore pressure generated by the LWAC slab at a heating rate of 10 °C/min was larger than that at 5 °C/min, that is, it increased from 96 KPa to 122 KPa. A similar trend was presented for the NWC slab, that is, it increased from 214 KPa to 363 KPa. Moreover, the NWC slab had a sudden pressure rise regardless of whether the heating rate was 5 or 10 °C/min, but this was especially pronounced when the heating rate was 10 °C/min. The pressure curves shows that a faster heating rate led to a faster pressure rise, as was the case for the LWAC slab. This trend was also observed at 30 and 50 mm from the heated surface (as shown in Figure 22b,c). Based on the above results, a higher heating rate would generate a larger pore pressure inside the concrete slab.



Figure 22. Effect of the heating rate on the pore pressure of the air-dried specimens performed at a target temperature of 600 $^{\circ}$ C: (a) 10; (b) 30; (c) 50 mm depths.

The evolution of the pore pressure when the target temperature was 800 °C, at a depth of 10 mm from the heated surface of the air-dried specimens, is shown in Figure 23a. It can be seen that both the LWAC and NWC slabs had larger pore pressures when the heating rate was 10 °C/min, and the pressure curves showed a steep rise. Examining the specimen shows that many cracks occurred at 10 mm from the heated surface. However, when the heating rate was 5 °C/min, the pressure curve was relatively flat, and the pressure value was also lower. At a distance of 30 mm from the heated surface (as shown in Figure 23b),

when the heating rate was 10 °C/min, the pore pressures of both the LWAC and NWC slabs increased rapidly. However, because more cracks generated at 10 mm, the internal steam escaped more easily; thus, the pore pressure was lower than that at a heating rate of 5 °C/min. This phenomenon was also observed at 50 mm from the heated surface, as shown in Figure 23c. The above results show that when the specimen is in an air-dried state, due to the large water content and high steam pressure during heating, cracks might be more likely to occur inside the specimen.



Figure 23. Effect of the heating rate on the pore pressure of the air-dried specimens performed at a target temperature of 800 $^{\circ}$ C: (a) 10; (b) 30; (c) 50 mm depths.

3.6. The Effect of the Moisture Content on the Pore Pressure3.6.1. Concrete Slabs Exposed to a Target Temperature of 600 °C

The moisture content of a concrete specimen represents the mass percentage of the moisture it contains, which is closely related to the increase in the pore pressure at high temperatures [63]. The evolution of the pore pressure at a depth of 10 mm from the heated surface of the concrete slab, at a target temperature of 600 °C and a heating rate of 5 °C/min, is shown in Figure 24a. The LWAC slabs had similar pressure curves in the oven-dried and air-dried states. The maximum pore pressures of the LWAC slabs in oven-dried and air-dried states were 102 and 96 KPa, respectively. However, the NWC slab had a higher pore pressure in the air-dried state, and there was an obvious peak value (214 KPa) and a steep pressure rise phenomenon after being heated for 2 h. This was due to the rapid rise in the pore pressure, which caused the internal fractures resulting in the gas escaping, causing the pressure value to drop rapidly. At 30 mm from the heated surface (as shown in Figure 24b), the pore pressure of the LWAC slab in the air-dried state was slightly higher than that in the oven-dried state, indicating that a higher water content led to a higher steam pressure. This is consistent with the data in the literature [62,64]. However, the NWC slab showed the opposite result at this depth. The reason for this might be that a large crack occurred at 10 mm and extended and expanded, which made it easier for the steam to escape here, resulting in a lower pore pressure. At 50 mm from the heated surface (as shown in Figure 24c), the pore pressure of the LWAC slab in the air-dried state was higher than that in the oven-dried state. In addition, Figure 24c shows that the high water content caused the pressure curve to be more unstable. The NWC slab also had the same trend.



Figure 24. Effect of the moisture content on the pore pressure of the specimens performed at a target temperature of 600 °C and heating rate of 5 °C/min: (a) 10; (b) 30; (c) 50 mm depths.

The evolution of the pore pressure at a depth of 10 mm from the heated surface of the concrete slab, at a target temperature of 600 °C and a heating rate of 10 °C/min, is shown in Figure 25a. The LWAC slabs had similar pressure curves in the oven drying and air-dried states. The maximum pore pressures of LWAC slabs in oven-dried and air-dried states were 102 and 96 KPa, respectively. However, the NWC slab had a higher pore pressure in the air-dried state and showed a pressure rise, which was the same as that at a heating rate of 5 °C/min at the same target temperature. At 30 mm from the heated surface (as shown in Figure 25b), the pore pressure difference of the LWAC slab under different moisture states was very small, and this phenomenon was also observed for the NWC slab.



Figure 25. Effect of the moisture content on the pore pressure of the specimens performed at a target temperature of 600 °C and heating rate of 10 °C/min: (**a**) 10; (**b**) 30; (**c**) 50 mm depth.

3.6.2. Concrete Slabs Exposed to a Target Temperature of 800 °C

The evolution of the pore pressure at a depth of 10 mm from the heated surface of the concrete slab, at a target temperature of 800 $^{\circ}$ C and a heating rate of 5 $^{\circ}$ C/min, is shown in Figure 26a. Both the LWAC and NWC slabs showed higher pore pressures in the oven-dried state. The maximum pore pressures of the LWAC slabs in oven-dried and air-dried states were 143 and 93 KPa, respectively. At 30 mm from the heated surface (as shown in Figure 26b), the LWAC slab also showed a higher pore pressure in the oven-dried state. However, the curves of the NWC slabs in the oven-dried and air-dried states were relatively close. At 50 mm from the heated surface (as shown in Figure 26c), the pore pressure of the LWAC slab in the air-dried state was significantly higher than that of the oven-dried state, while the NWC slab showed no significant difference. The results show that, at a lower heating rate, the pore pressures of the LWAC specimens with different moisture contents near the heated surface were not significantly different. This is because the slower heating rate allowed the water vapor near the heated surface to have sufficient time to gradually transport into the interior of the specimen through the internal pores. However, at a deeper distance from the heated surface, because LWAC had more pores, its internal water content was larger in the air-dried state. In addition, the water vapor



near the heated surface was transported to the back of the specimen due to the heating, resulting in a more significant increase in the pore pressure in the deeper part.

Figure 26. Effect of the moisture content on the pore pressure of the specimens performed at a target temperature of 800 °C and a heating rate of 5 °C/min: (a) 10; (b) 30; (c) 50 mm depths.

The evolution of pore pressure at a depth of 10 mm from the heated surface of the concrete slab, at a target temperature of 800 °C and a heating rate of 10 °C/min, is shown in Figure 27a. The LWAC slab showed a high pore pressure in the air-dried state, and the pressure suddenly rose and then dropped sharply. This was because of the increase in the pore pressure due to the rapid evaporation of water vapor under the condition of a higher heating rate with a higher moisture content. The maximum pore pressures of the LWAC slabs in oven-dried and air-dried states were 344 and 893 KPa, respectively. The NWC slab also showed a similar trend. However, at a distance of 30 mm from the heated surface (as shown in Figure 27b), the LWAC and NWC slabs showed higher pore pressures in the oven-dried state, which was different from the results at 10 mm. The reason for this might be that the pore pressure at 10 mm in the air-dried state rapidly rose, resulting in cracks in the specimen, which caused the steam here to escape more easily; thus, the pore pressure was lower. At a distance of 50 mm from the heated surface (as shown in Figure 27c), the LWAC slab showed a higher pore pressure in the air-dried state, while the NWC slab showed no obvious difference.



Figure 27. Effect of the moisture content on the pore pressure of the specimens performed at a target temperature of 800 $^{\circ}$ C and heating rate of 10 $^{\circ}$ C/min: (**a**) 10; (**b**) 30; (**c**) 50 mm depths.

3.7. The Maximum Pore Pressure under Different Test Conditions

The maximum pore pressure (P_{max}) of each measuring point of the concrete slab under different test conditions is shown in Figure 28. Under the conditions of an oven-dried state, a target temperature of 600 °C, and a heating rate of 5 °C/min, the P_{max} of the LWAC slab was 102 kPa, which occurred at a distance of 10 mm from the heated surface. However, the P_{max} of the NWC slab was 138 kPa, which occurred at 30 mm from the heated surface. Under the conditions of an oven-dried state, a target temperature of 800 °C, and a heating rate of 5 °C/min, the P_{max} of the LWAC and NWC slabs both occurred at a distance of 30 mm from the heated surface, and their values were 153 and 194 kPa, respectively. Under the conditions of an oven-dried state, a target temperature of 600 °C, and a heating rate of 10 °C/min, the P_{max} of the LWAC slab was 126 kPa, which occurred at 10 mm from the heated surface. The P_{max} of the NWC slab was 138 kPa, which occurred at 30 mm from the heated surface. However, under the conditions of an oven-dried state, a target temperature of 800 °C, and a heating rate of 10 °C/min, the LWAC slab could not obtain its actual P_{max} due to the fact of spalling. The recorded data were 344 kPa, which occurred 10 mm from the heated surface. Under the same test conditions, the P_{max} of the NWC slab occurred at 30 mm from the heated surface, and its value was 310 kPa.



Figure 28. The measured maximum pore pressure under different test conditions: (a) LWAC in an oven-dried state; (b) LWAC in an air-dried state; (c) NWC in an oven-dried state; (d) NWC in an air-dried state.

On the other hand, under the conditions of an air-dried state, a target temperature of 600 °C, and a heating rate of 5 °C/min, the P_{max} of the LWAC and NWC slabs occurred at 30 and 10 mm from the heated surface, respectively. It is worth noting that the P_{max} of the LWAC slabs at three different depths was almost the same, ranging from 96 to 97 kPa. Under the conditions of an air-dried state, a target temperature of 800 °C, and a heating rate of 5 °C/min, the P_{max} of the LWAC and NWC slabs occurred at 50 and 30 mm from the heated surface, respectively. Among them, the P_{max} of the LWAC slab was 469 kPa, and the P_{max} of the NWC slab was 192 kPa. This result shows that a higher target temperature would cause its P_{max} to appear further from the heated surface. The design strength of the LWAC and NWC slabs was 40 MPa, but the strength of the LWA was lower than that of the normal-weight aggregate. Therefore, its matrix was bound to have high strength and compactness. In other words, it was relatively less permeable, which might lead to higher pore pressures. Under the conditions of an air-dried state, a target temperature of 600 °C, and a heating rate of 10 °C/min, the P_{max} of the LWAC and NWC slabs occurred at

50 and 10 mm from the heated surface, respectively. In addition, under the conditions of an air-dried state, a target temperature of 800 °C, and a heating rate of 10°C/min, the P_{max} of both the LWAC and NWC slabs occurred at 10 mm from the heated surface. Among them, the P_{max} of the LWAC slab was 2121 kPa, which was significantly higher than that of the NWC slab, which was 363 kPa. This is the same result as the specimen in the air-dried state at a heating rate of 5 °C/min.

Figure 29 shows the time required to reach the maximum pore pressure in the concrete slabs at different depths under different experimental variables. Overall, at all depths, the time required to reach the maximum pore pressure was relatively short with a heating rate of 10 $^{\circ}$ C/min, while a longer time was required with a heating rate of 5 $^{\circ}$ C/min. This indicates that the moisture was quickly driven to the deeper areas of the concrete in terms of the heating rate. It is clear, therefore, that the vapor transport rate was faster at high heating rates and slower at low heating rates. This is consistent with the findings of Bangi and Horiguchi [46].





4. Conclusions

In this study, the thermo-mechanical process and thermo-hygral process of lightweight concrete slabs exposed to high temperatures were analyzed under different experimental variables. The combination of thermal stress and vapor pressure induced the spalling of some specimens. Based on the test results, the following conclusions can be drawn:

 Under the same test variables, the temperature distribution trend of the LWAC slab was different from that of the NWC slab. At a target temperature of 600 °C and a heating rate of 5 °C/min, the oven-dried LWAC slab had a maximum temperature of 368.2 °C at a depth of 10 mm, while the oven-dried NWC slab had a maximum temperature of 338.6 $^{\circ}$ C at a depth of 10 mm. This shows that the maximum temperature of the LWAC slab at a depth of 10 mm was 8.7% higher than that of the NWC slab;

- At 10 mm from the heated surface, the maximum pore pressure of the LWAC slabs was generally higher than that of the NWC slabs, while there was an opposite trend at 30 and 50 mm from the heating surface. At a target temperature of 600 °C and a heating rate of 5 °C/min, the maximum pore pressure at a depth of 10 mm for the LWAC slab was 102 KPa, while that of the NWC slab was 85 KPa. This shows that the maximum temperature of the LWAC slab at a depth of 10 mm was 20% higher than that of the NWC slab;
- As the heating rate increased, a higher pore pressure was generated inside the concrete and the pressure rose more rapidly. The peak value of the measured pore pressure was reached in the vaporization temperature range. This result suggests that the vaporization of water into the concrete was responsible for the increase in the pore pressure;
- When the moisture content of the specimen increased, the maximum pore pressure
 of the LWAC slabs occurred at a deeper position from the heated surface, while it
 occurred closer to the heated surface in the NWC slabs;
- As the concrete specimen was exposed to high temperatures, a higher moisture content and a faster heating rate increased the probability of spalling. In particular, at a target temperature of 800 °C and a heating rate of 10 °C/min, the corner spalling phenomenon appeared on the air-dried LWAC slab.

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